Data driven approaches to learning about nuclear structure

David Jenkins

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United Kingdom National Nuclear Laboratory
AWE NUCLEAR SECURITY TECHNOLOGIES
UK Atomic Energy Authority
NSG

kromek safer and healthier world
BAE SYSTEMS
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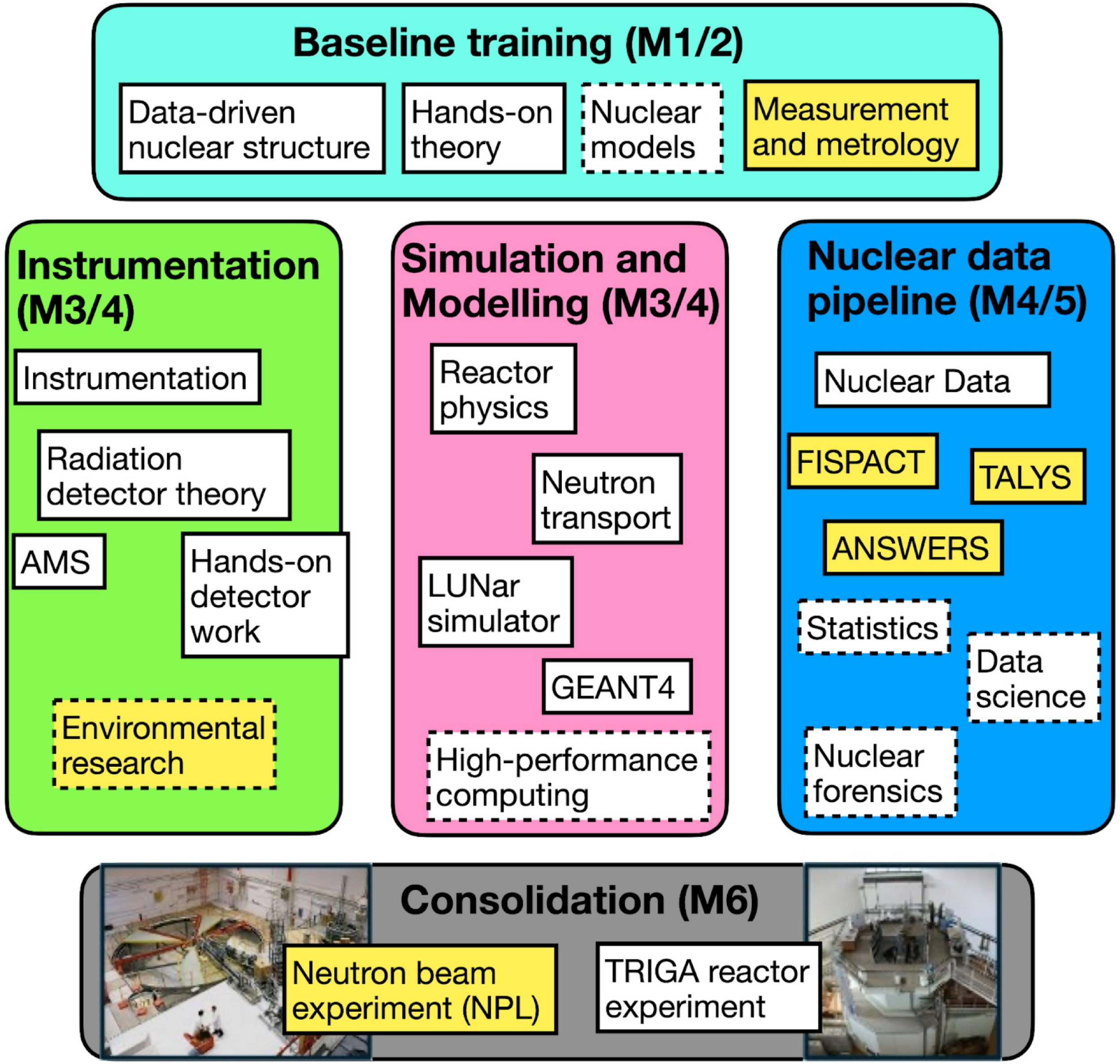
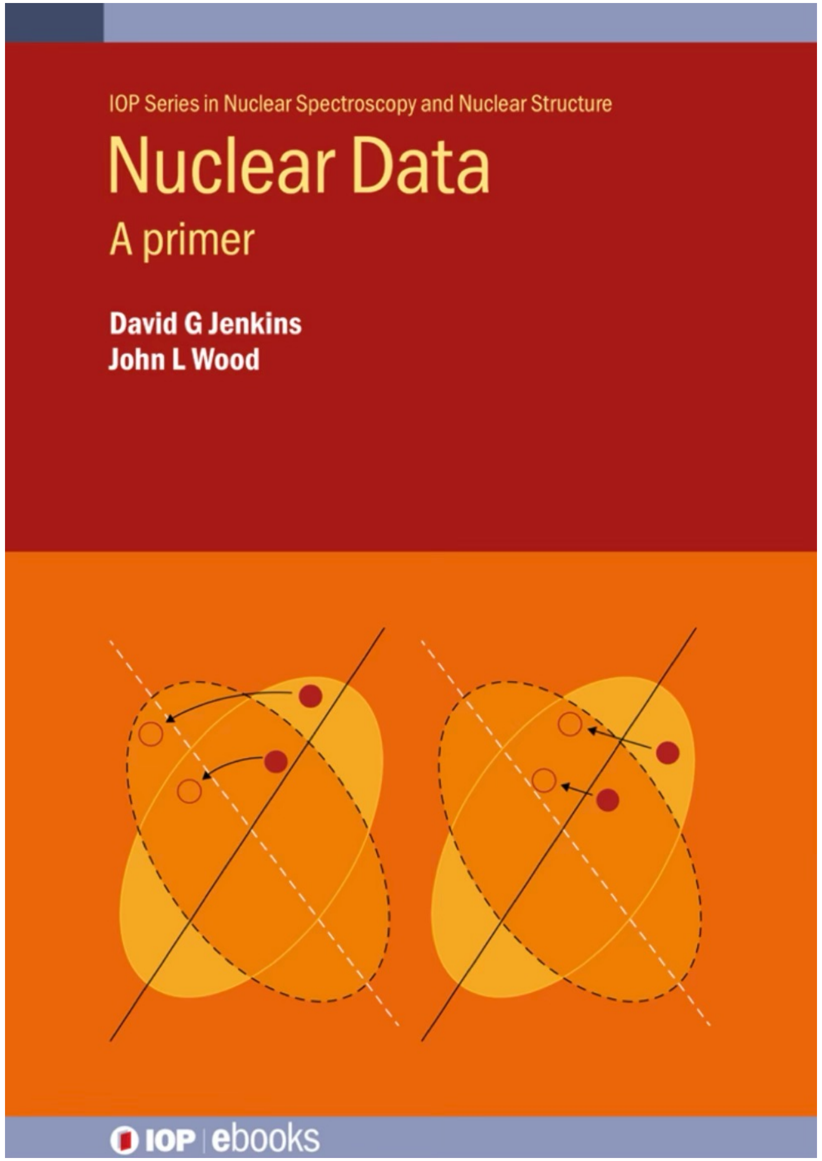


Baseline training (M1/2)
Data-driven nuclear structure
Hands-on theory
Nuclear models
Measurement and metrology
Instrumentation (M3/4)
Instrumentation
Radiation detector theory
AMS
Hands-on detector work
Environmental research
Simulation and Modelling (M3/4)
Reactor physics
Neutron transport
LUNar simulator
GEANT4
High-performance computing
Nuclear data pipeline (M4/5)
Nuclear Data
FISPACT
TALYS
ANSWERS
Statistics
Data science
Nuclear forensics
Consolidation (M6)
Neutron beam experiment (NPL)
TRIGA reactor experiment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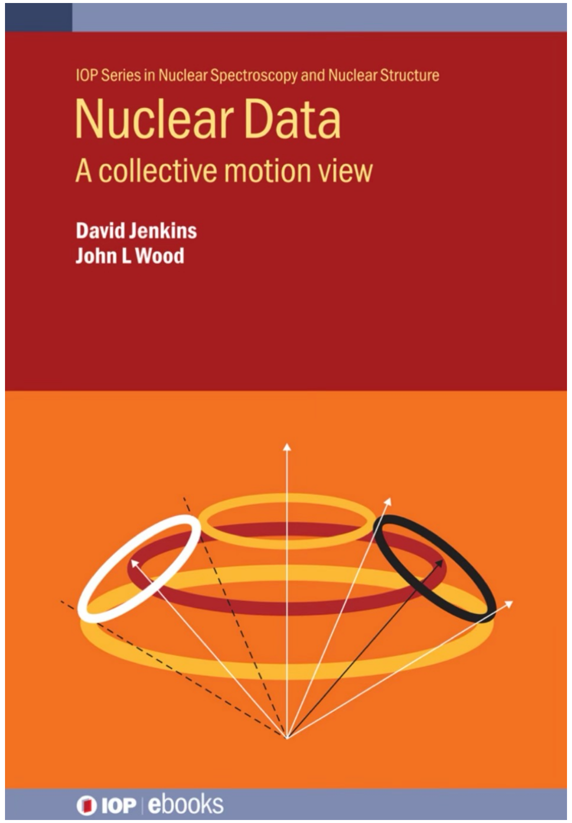
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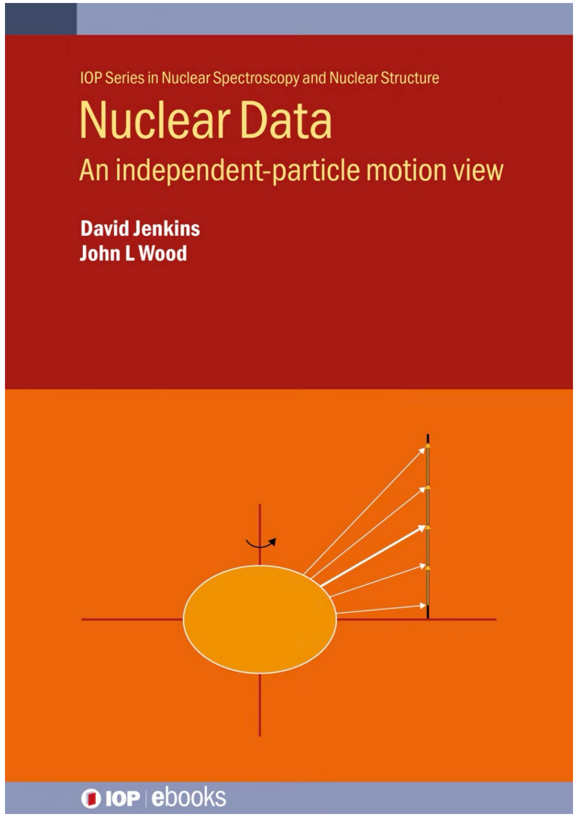
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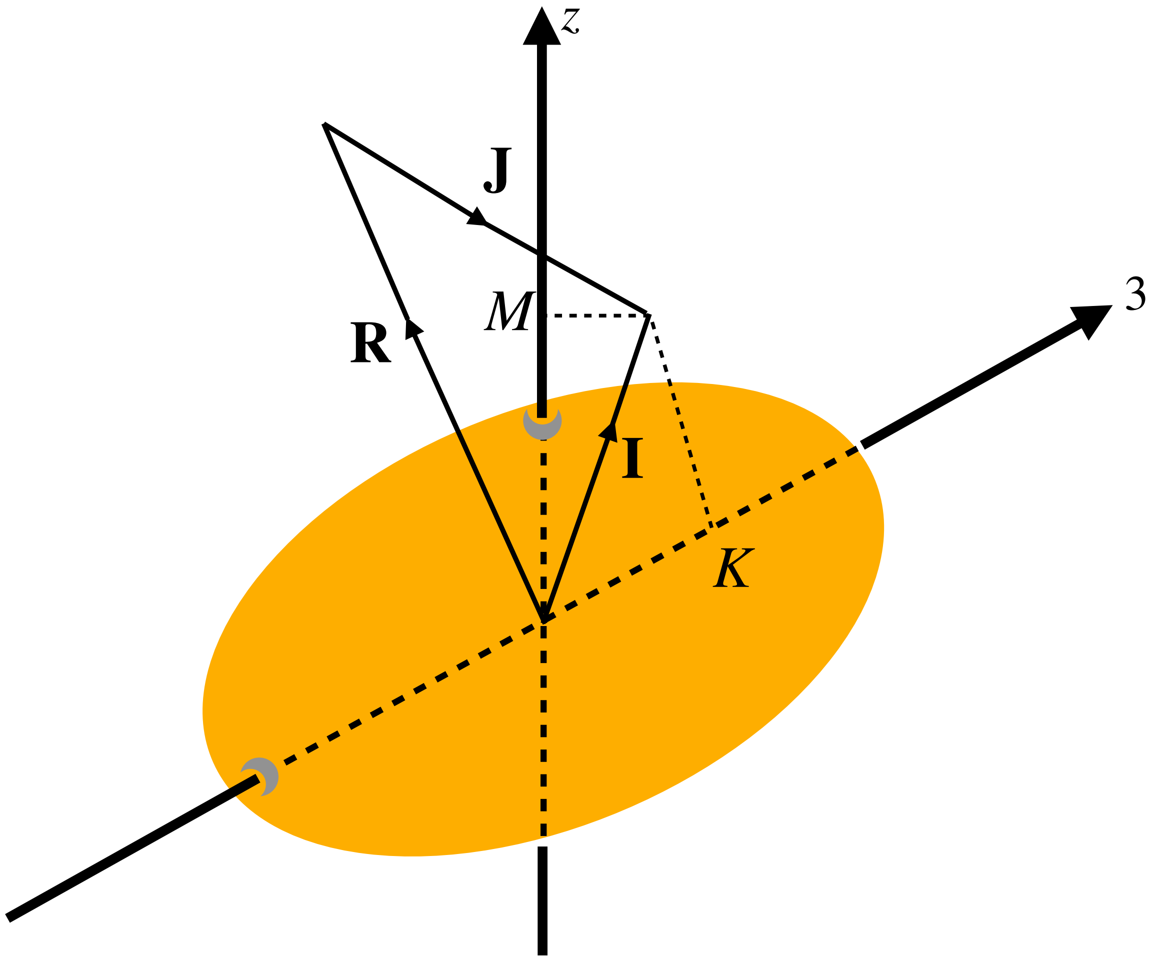
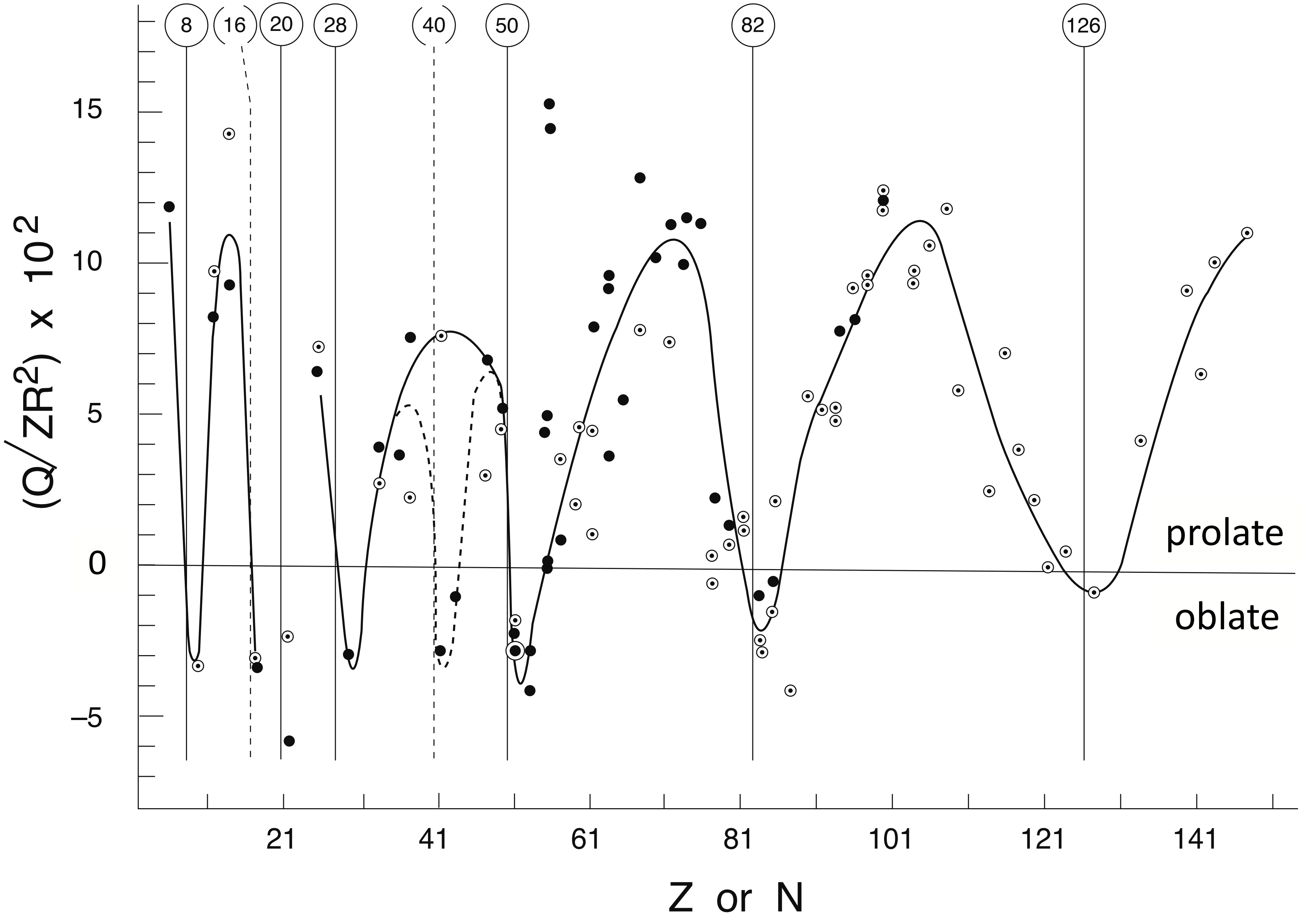
How well defined are rotations in nuclei?





- NB Q is only defined for states with $J \geq 1$

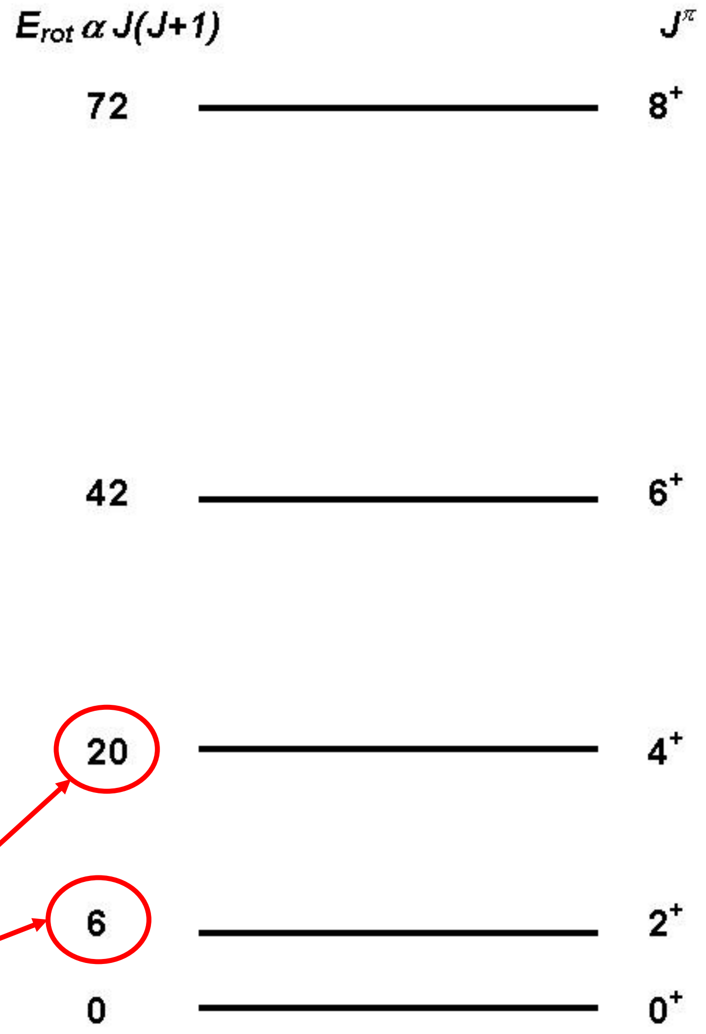
Rotational bands even-even nuclei

For the special case of even-even nuclei only even J values are allowed in a rotational band built upon the $J^{\pi}=0^{+}$ ground states (due to some symmetry properties)

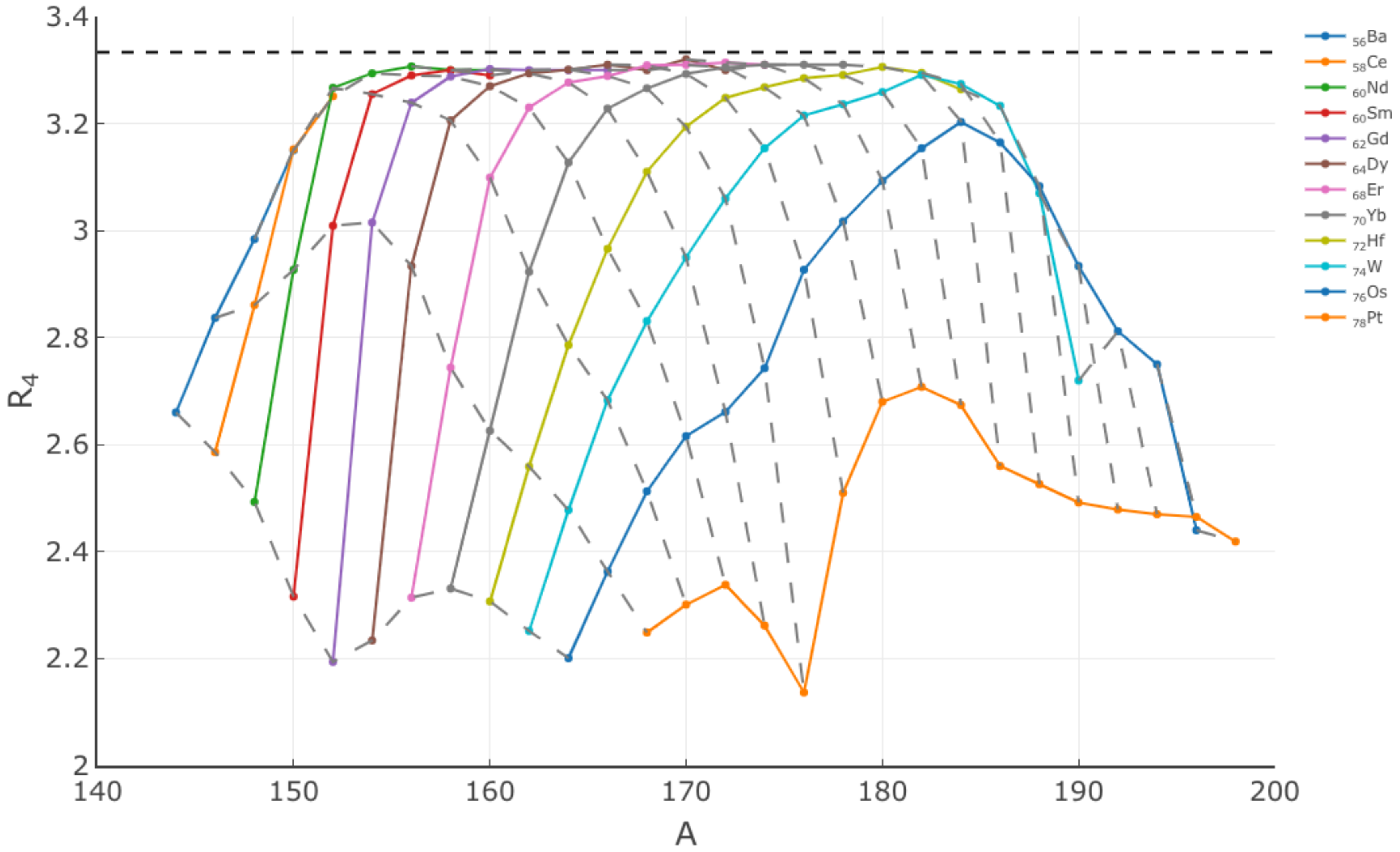
Thus, for an even-even nucleus with a fixed deformation (i.e. a fixed moment of inertia) we expect to find a level scheme like this

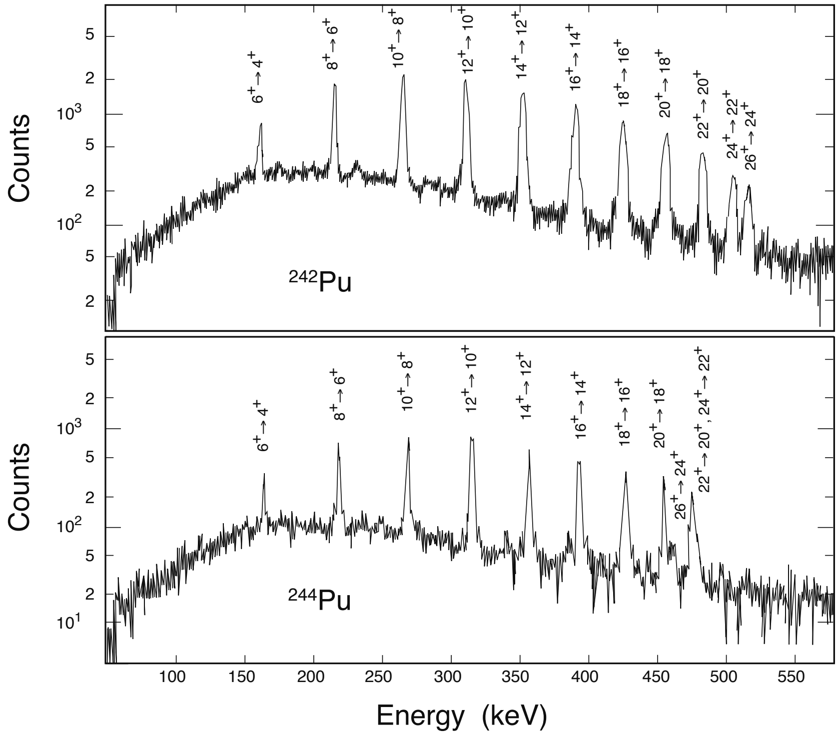
A structure of excited states such as this in known as a **rotational band, states within the band are known as "band members" and the lowest-E state is the "band head"**

So we expect $E(4_1^+)/E(2_1^+) \approx 3.33$

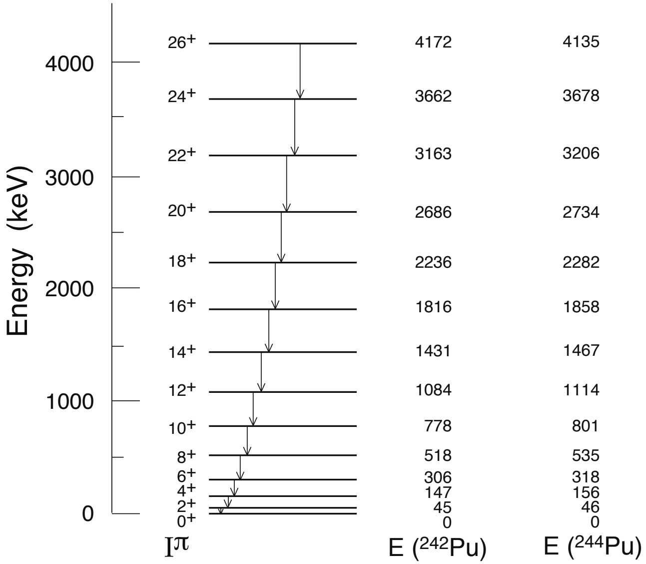


$R_4 = E(4^+)/E(2^+)$

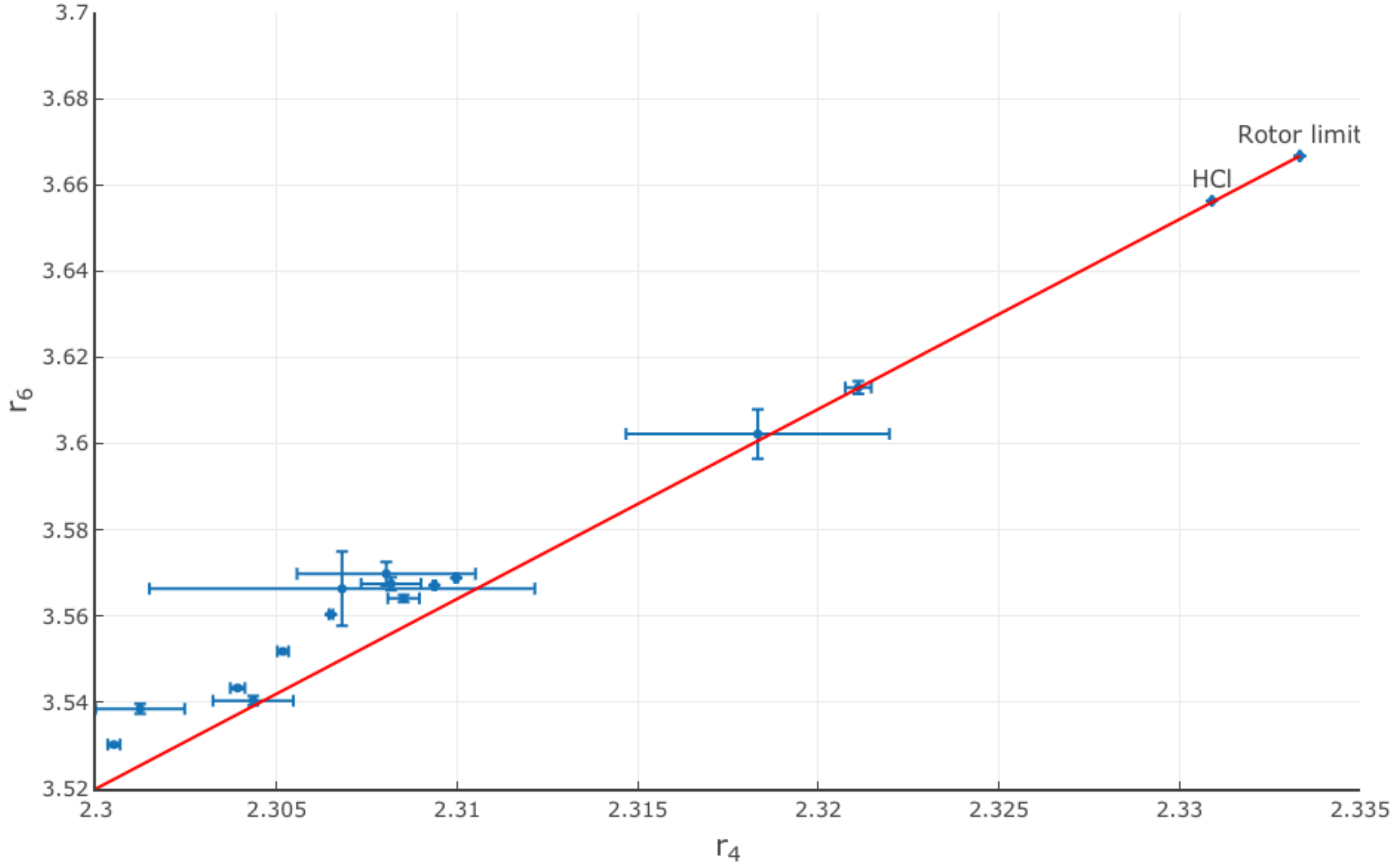

3.4
3.2
3
2.8
2.6
2.4
2.2
2
R4
140
150
160
170
180
190
200
A
56Ba
58Ce
60Nd
60Sm
62Gd
64Dy
68Er
70Yb
72Hf
74W
76Os
78Pt



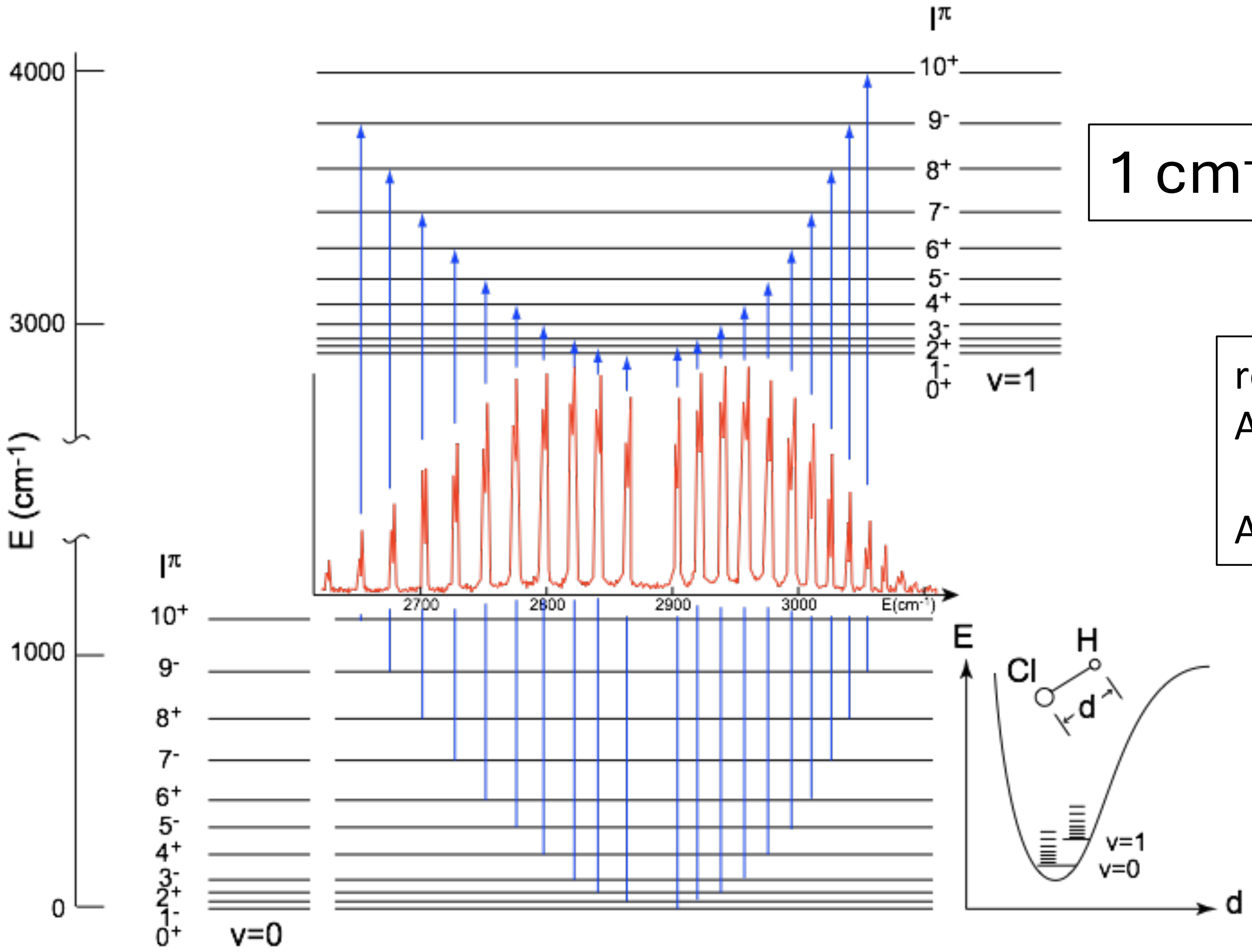
$$E = \frac{\hbar^2 I(I+1)}{2\mathscr{J}}$$



$$r_6 := \frac{E(6_1^+) - E(4_1^+)}{E(2_1^+)} \text{ vs. } r_4 := \frac{E(4_1^+) - E(2_1^+)}{E(2_1^+)},$$



The infrared absorption spectrum of HCl reveals molecular vibrations and rotations.



$1\ cm^{-1} = 1.24 \times 10^{-4}\ eV$

rotational const.

$A_1 = 10.134\ cm^{-1}$

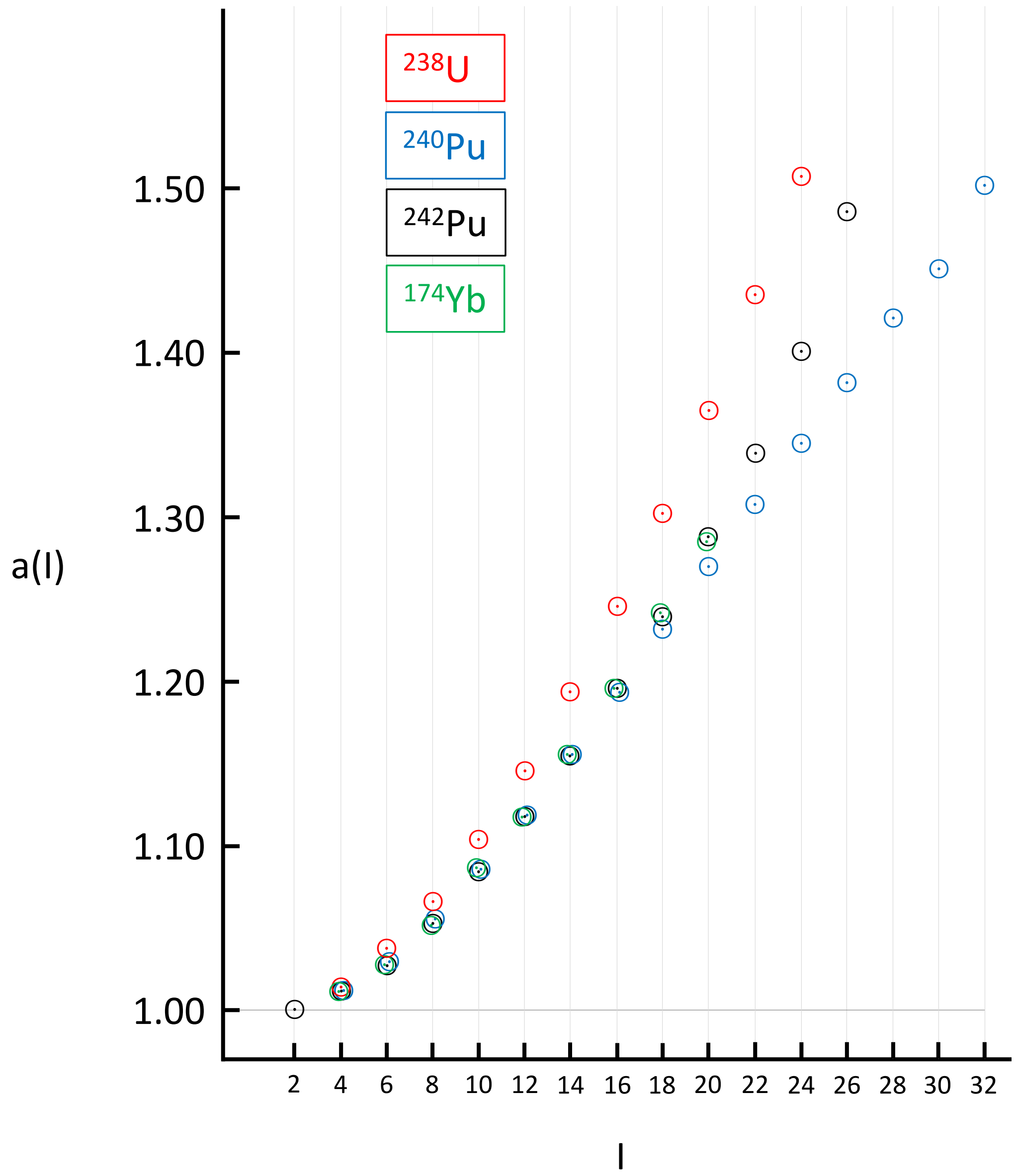
$A_0 = 10.437\ cm^{-1}$

We can also explore the deviation from rotor behaviour as a function of I to very large values of angular momentum using the rotational parameter:

$$a(I) := [E_\gamma(I \rightarrow I-2)/(4I-2)]/[E_\gamma(2 \rightarrow 0)/6]$$

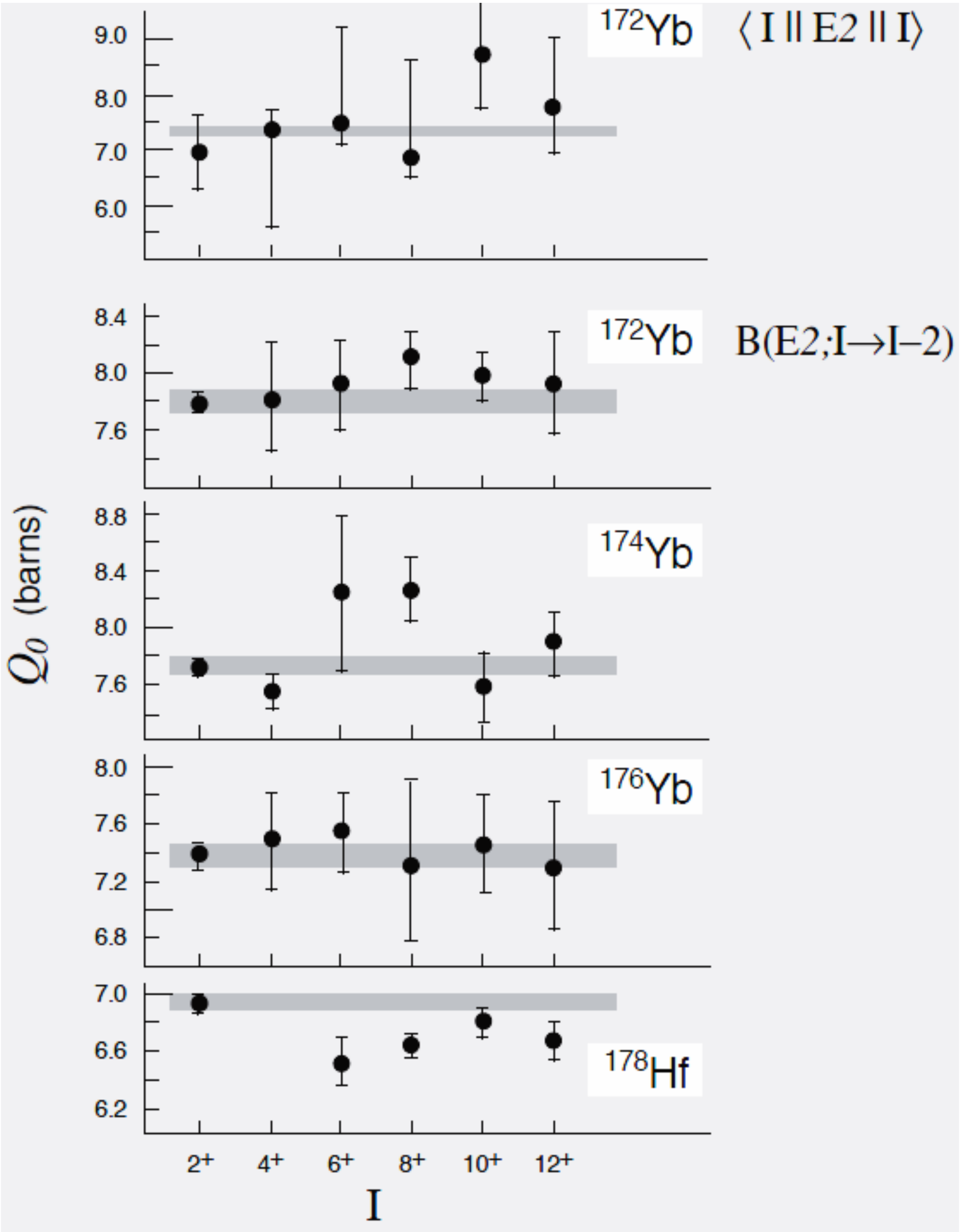
This parameter should be unit for all values of I if the rotor model were perfectly respected.

For discussion: what is fascinating is that the rotational parameter for ^{174}Yb and ^{242}Pu are almost identical despite the very large difference in number of protons and neutrons making up the nucleus!



See just how similar ^{242}Pu and ^{174}Yb are when energies are scaled

I_i	E(^{242}Pu) (keV)	E(^{174}Yb) (keV) $\times$ 0.5824	E(^{174}Yb) (keV)	% dev.
2	44.54^{2}	44.54 [norm.]	76.471^{1}	-
4	102.8^{1}	102.9	176.645^{2}	+0.098
6	159.0^{1}	158.9	272.918^{6}	-0.063
8	211.7^{4}	211.8	363.64^{5}	+0.047
10	260.5^{6}	260.4^{6}	447.2^{10}	-0.038
12	305.8^{8}	305.4^{8}	524.4^{13}	-0.131
14	347.3^{10}	347.1^{10}	595.9^{17}	-0.058
16	385.0^{11}	384.4^{11}	660^{2}	-0.156
18	419.3^{12}	418.7^{17}	719^{3}	-0.143
20	450.2^{13}	450.8^{29}	774^{5}	+0.133
				-0.035 (avg.)



172Yb
⟨I ‖ E2 ‖ I⟩
172Yb
B(E2;I→I–2)
174Yb
176Yb
178Hf
Q0 (barns)
9.0
8.0
7.0
6.0
8.4
8.0
7.6
8.8
8.4
8.0
7.6
8.0
7.6
7.2
6.8
7.0
6.6
6.2
2+
4+
6+
8+
10+
12+
I

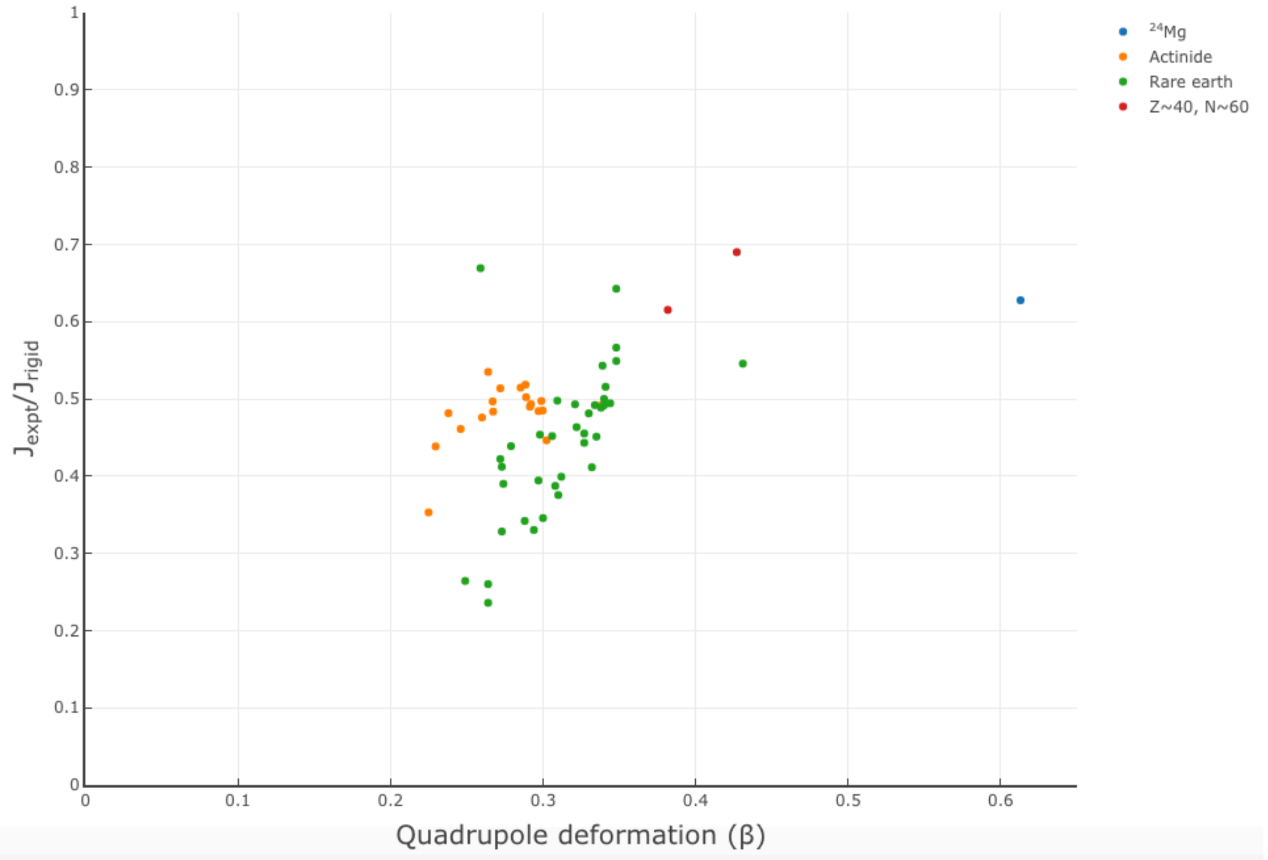
An experimental moment of inertia can be derived from the excitation energy of the 2+ state. Theoretical moments of inertia can be extracted for two different scenarios of rigid rotor and irrotational flow and compared to experiment.

$$\mathscr{I}_{\text{expt}} = 0.2080 \times 10^{-54} E(2_1^+)^{-1} [\text{MeV}^{-1}],$$
$$\mathscr{I}_{\text{rigid}} = 0.8864 \times 10^{-57} A^{5/3} (1 + 0.3154\beta + 0.44\beta^2),$$
$$\mathscr{I}_{\text{irrot}} = 0.8864 \times 10^{-57} A^{5/3} 0.8951\beta^2,$$

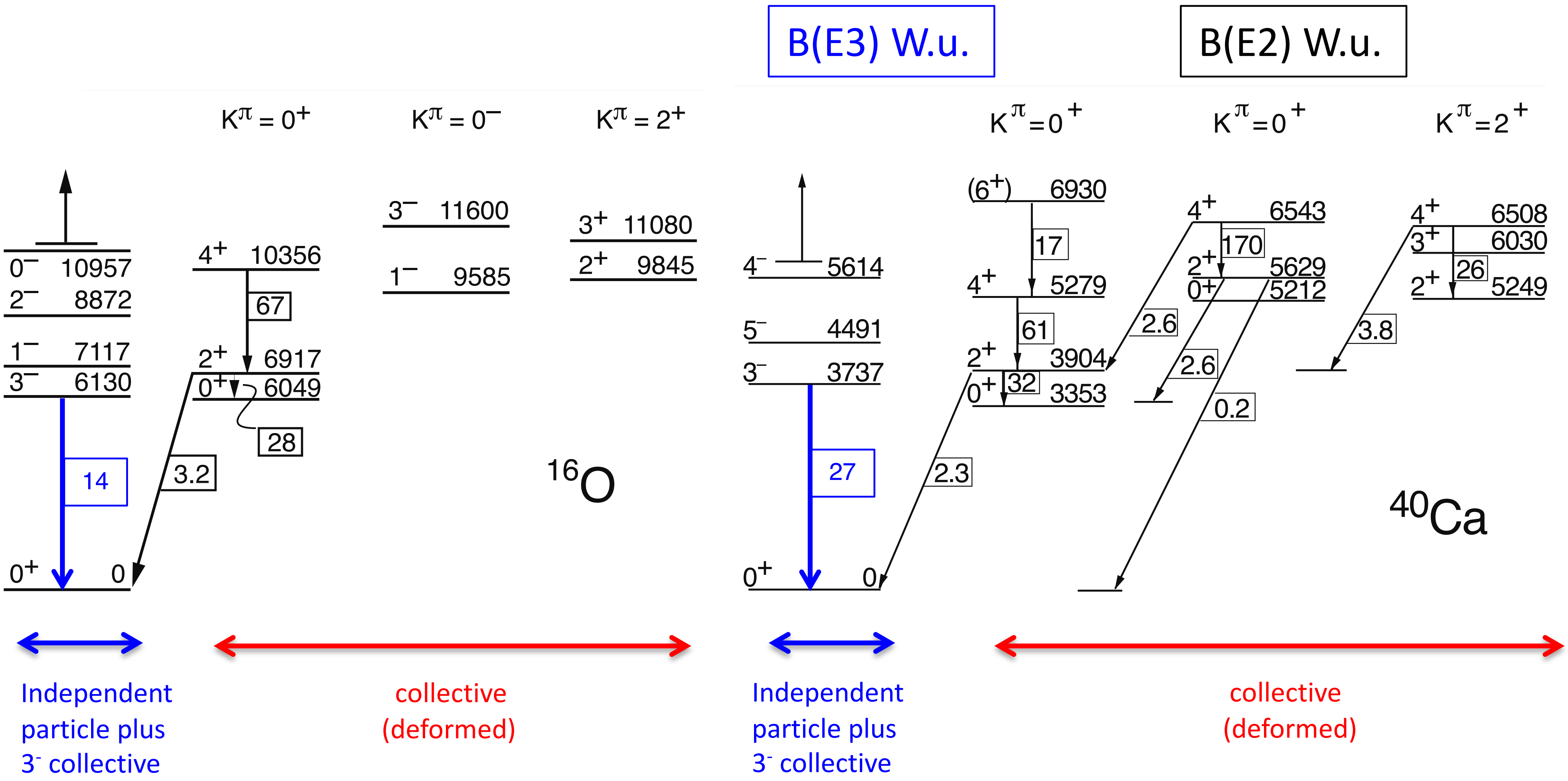
$$\beta = Q_0 \frac{\sqrt{5\pi}}{3ZR^2},$$

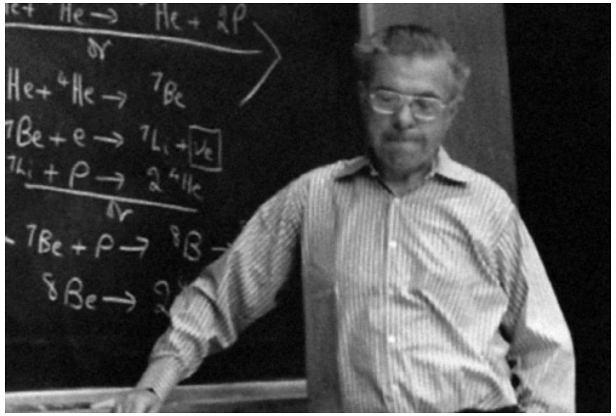
The figure shows that the experimental value is never more than about 0.3-0.7 of the rigid rotor value.

CONCLUSION: Everything looks like rotation but it's nothing like a classical rotating rigid body. What is actually rotating is a very good question!



	Z	Q_0 (b)	$A^{2/3}$	β	$\mathscr{I}_{rigid}$ $\times 10^{-54}$ (kg.m^2)	$E(2_1^+)$ (keV)	$\mathscr{I}_{expt}$ (kg.m^2)	$\frac{\mathscr{I}_{expt}}{\mathscr{I}_{rigid}}$
^{174}Yb	70	7.82[5]	31.167	0.3081	5.955 $\times 10^{-54}$	76.471[1]	2.723 $\times 10^{-54}$	0.4573
^{242}Pu	94	11.90[6]	38.834	0.2823	10.184 $\times 10^{-54}$	44.54[2]	4.675 $\times 10^{-54}$	0.4591
^{152}Dy	66	17.5[2]	28.482	0.7076	6.025 $\times 10^{-54}$	33.75	6.170 $\times 10^{-54}$	1.024

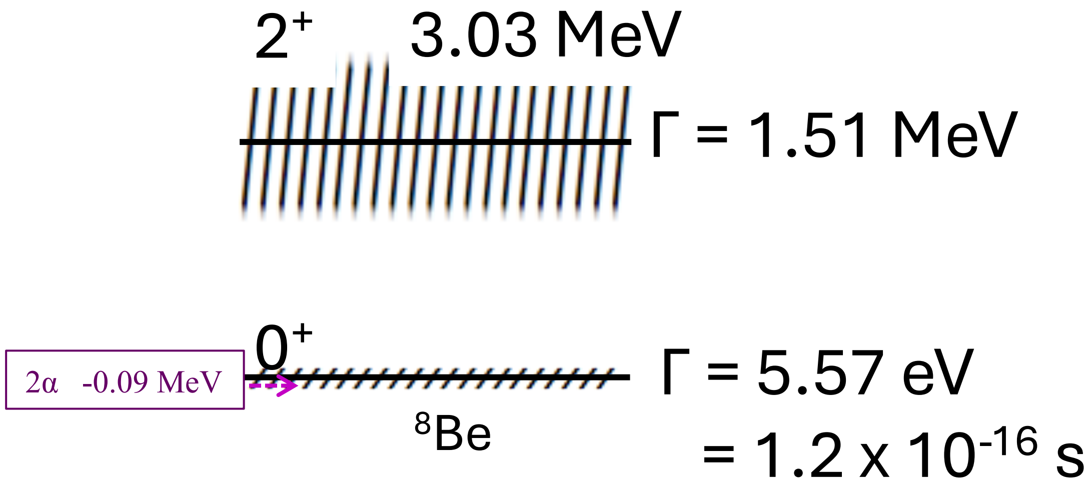

B(E3) W.u.
B(E2) W.u.
Kπ = 0+
Kπ = 0−
Kπ = 2+
0− 10957
2− 8872
1− 7117
3− 6130
0+ 0
14
4+ 10356
67
2+ 6917
0+ 6049
28
3.2
3− 11600
1− 9585
3+ 11080
2+ 9845
16O
4− 5614
5− 4491
3− 3737
0+ 0
27
(6+) 6930
17
4+ 5279
61
2+ 3904
0+ 3353
32
2.3
4+ 6543
170
2+ 5629
0+ 5212
2.6
2.6
0.2
4+ 6508
3+ 6030
26
2+ 5249
3.8
40Ca
Independent
particle plus
3- collective
collective
(deformed)
Independent
particle plus
3- collective
collective
(deformed)

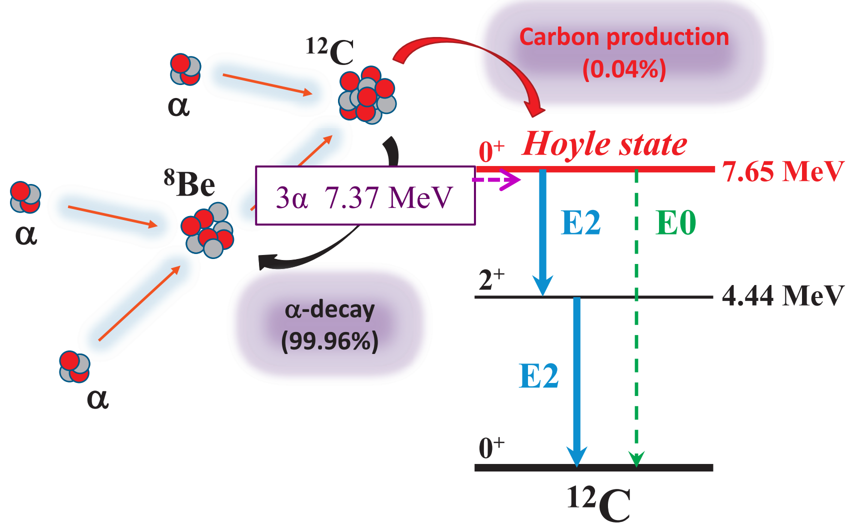


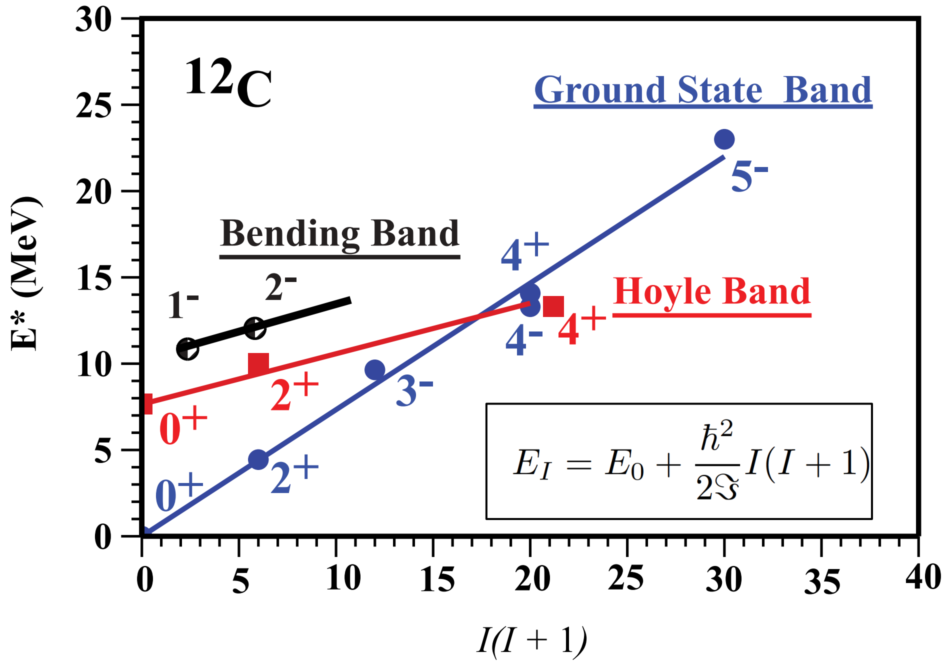
Sir Fred Hoyle (1915-2001)

Helium fusion in stars

F. Hoyle, Astrophysical J. Suppl. Ser. **1** 121 1954







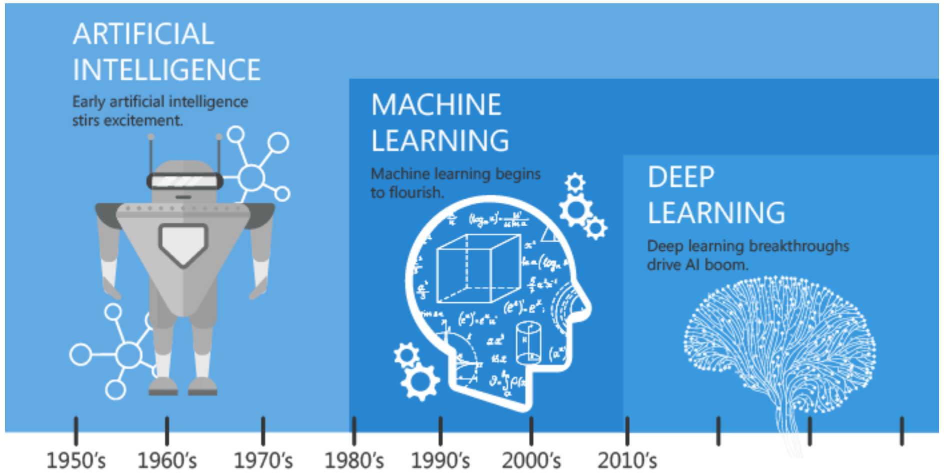
A few parting questions….

1) Do we need more data?

2) If so, what kind of data do we need?

3) Are we doing enough with the data we have?

How to use the amazing resources on NNDC?



Adopted Levels, Gammas

History

Type	Author	Citation	Literature Cutoff Date
Full Evaluation	M. Shamsuzzoha Basunia, Anagha Chakraborty	NDS 186, 2 (2022)	31-Mar-2022

Q(β^-)=−13884.77 *23*; S(n)=16531.22 *3*; S(p)=11692.69 *1*; Q(α)=−9316.56 *1* 2021Wa16
S(2n)=29676.23 *16*, S(2p)=20486.805 *22* (2021Wa16).

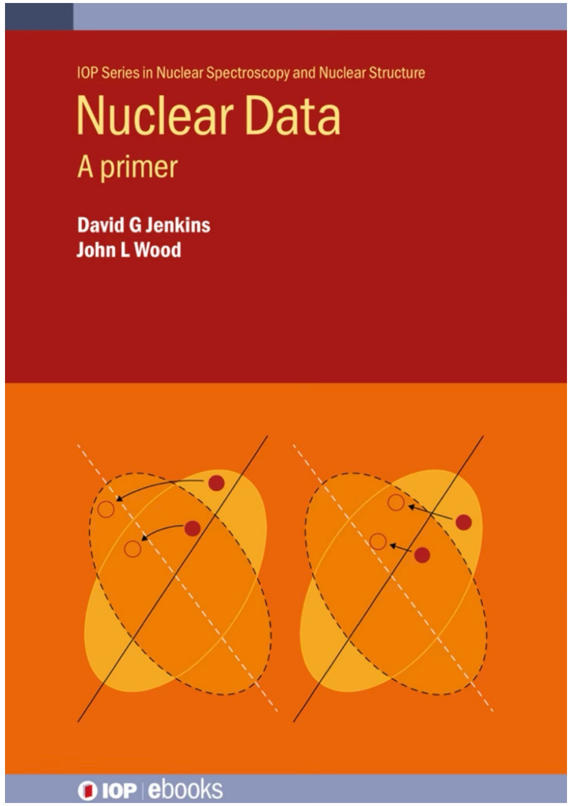
Other reactions:
2004Be18, 2004Be08: ^{12}C(^{24}Mg, ^{12}C), E=130 MeV; measured Eγ, (particle)γ-coin.
2011Fr14: ^{12}C(^{13}C,n) E=12, 13.5, 20 MeV; measured reaction products ^{25}Mg; deduced ^{24}Mg excited states and reported resonance energies at 13.25 MeV *20* and 14.25 MeV *20*.
2001Di12: ^{11}B(^{13}N,X), (^{13}N,^{12}C), E=29.5, 45 MeV. Measured particle spectra, fusion σ. Deduced ^{24}Mg 6−α decay features, isospin purity/mixing in ^{24}Mg at excitation energy ~47 MeV, GDR γ-emission features.
2006Va20: ^{28}Si(p,p′X)^{24}Mg, E=1 GeV; measured Eγ; deduced σ.

^{24}Mg Levels

Cross Reference (XREF) Flags

A	^{24}Na β^- decay (14.956 h)	N	^{20}Ne(α,γ):Resonances		Others:
B	^{24}Na β^- decay (20.18 ms)	O	^{20}Ne(α,α),(α,α'):Resonances	AA	Coulomb excitation
C	^{24}Al ε decay (2.053 s)	P	^{20}Ne(^{6}Li,d),(^{7}Li,t)	AB	^{24}Mg($\alpha,\alpha'\gamma$)
D	^{24}Al ε decay (130.7 ms)	Q	^{22}Ne(^{3}He,n)	AC	^{24}Mg(^{6}Li,^{6}Li′)
E	^{25}Si εp decay	R	^{23}Na(p,γ),(p,p′),(p,X),	AD	^{24}Mg(^{16}O,^{16}O′)
F	^{26}P ε2p decay	S	^{23}Na(^{3}He,d),(^{3}He,dγ)	AE	^{25}Mg(p,d)
G	^{28}P $\varepsilon\alpha$ decay	T	^{24}Mg(γ,γ')	AF	^{25}Mg(^{3}He,^{4}He)
H	^{12}C(^{12}C,γ)	U	^{24}Mg(e,e′)	AG	^{27}Al(μ^-,ν3nγ)
I	^{12}C(^{12}C,p):Resonances	V	^{24}Mg($\pi^+,\pi^{+\prime}$),($\pi^-,\pi^{-\prime}$)	AH	^{27}Al(p,α)
J	^{12}C(^{14}N,d)	W	^{24}Mg(p,p′),(pol p,p′),	AI	^{28}Si(d,^{6}Li)
K	^{12}C(^{24}Mg,^{12}Cγ)	X	^{24}Mg(n,n′γ)	AJ	^{28}Si(^{28}Si,Xγ)
L	^{12}C(^{16}O,α),(^{16}O,$\alpha\gamma$)	Y	^{24}Mg(^{3}He,^{3}He′)		
M	^{12}C(^{24}Mg,2^{12}C),(^{20}Ne,2^{12}C)	Z	^{24}Mg(α,α')		

E(level)[†]	J$^\pi$	T$_{1/2}$ or Γ[j]	XREF	Comments
0[p]	0$^+$	stable	ABCDEFGH JKL N PQRSTUVWXYZ	XREF: Others: AA, AB, AD, AE, AF, AG, AH, AI, AJ δ<r^2>(^{26}Mg,^{24}Mg)=+0.140 fm^2 *5* (stat) *25* (syst) (2012Yo01). <r^2>$^{1/2}$(^{24}Mg)=3.0570 *16* (charge radius) (2013An02 evaluation). Others: 3.0570 fm *7* (stat) *48* (syst) (2012Yo01), 3.030 fm *30* (1971Li26 – (e,e′)).
1368.667[p] *5*	2$^+$	1.36 ps *3*	A CDEF H JKL N PQRSTUVWXYZ	XREF: Others: AA, AB, AC, AD, AE, AF, AG, AH, AI, AJ μ=+1.08 *3*; Q=−0.29 *3*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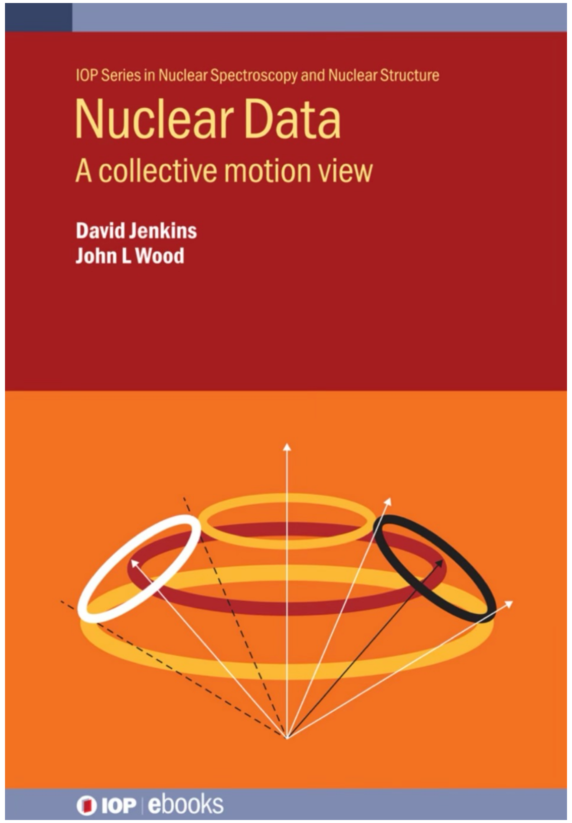
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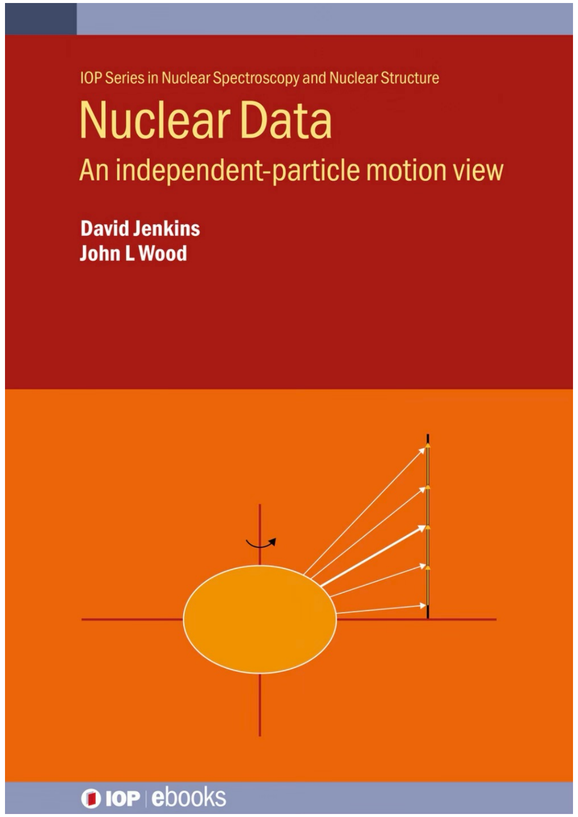
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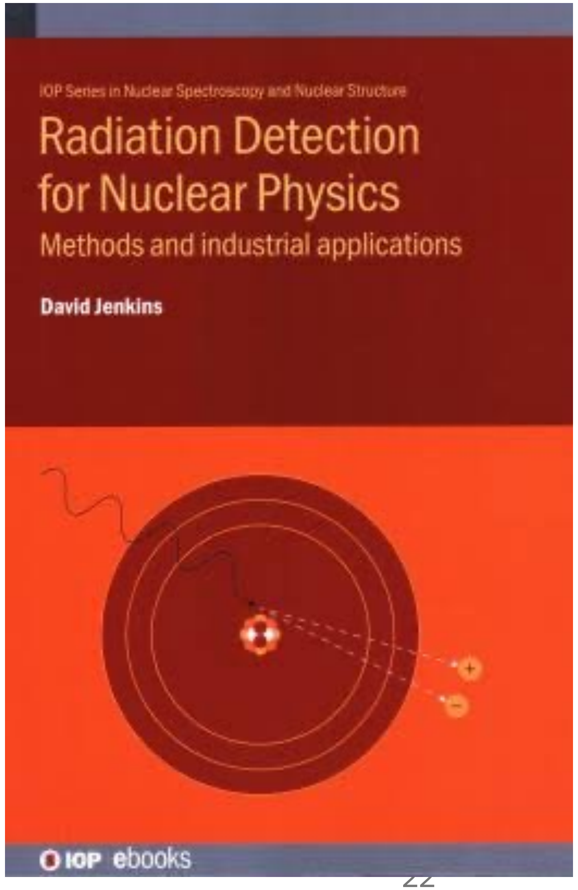
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Finis

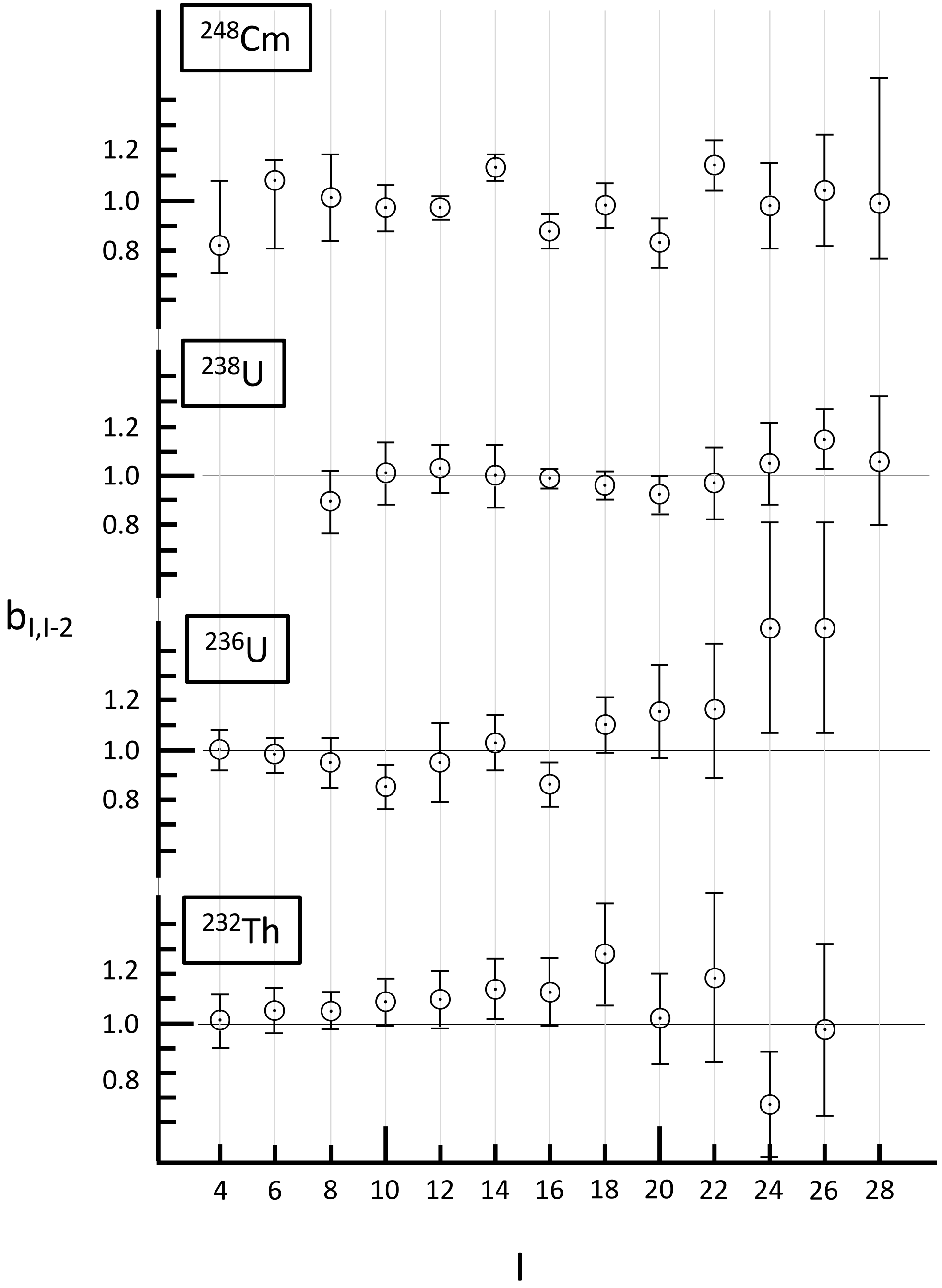
There should be a fixed relationship between B(E2) transition strengths up a rotational band

$$\frac{B_{I,I-2}}{B_{20}} = \frac{15I(I-1)}{2(2I-1)(2I+1)} := f(I)$$

We then define

$$b_{I,I-2} := B_{I,I-2}/B_{20}f(I)$$

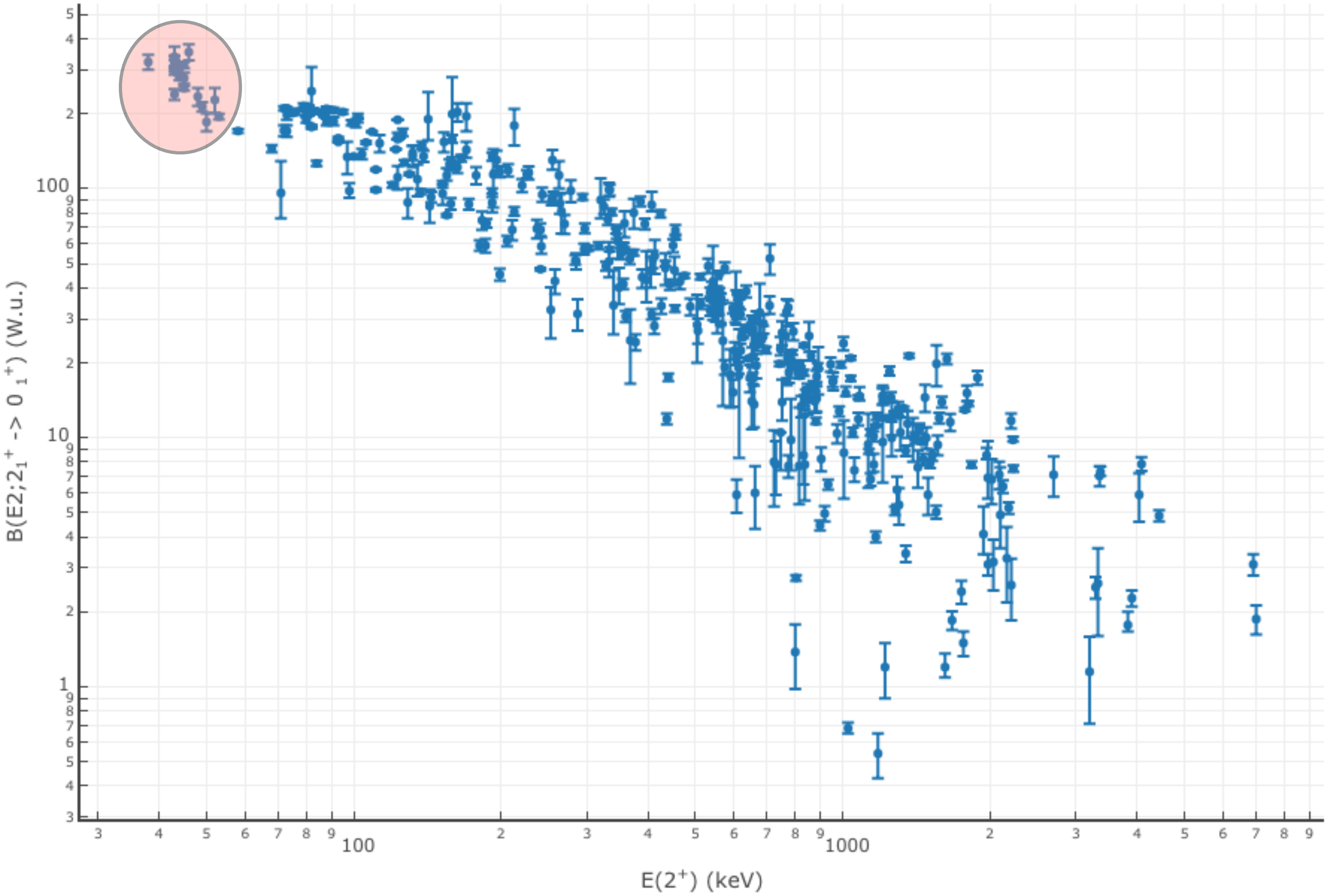
which should be unity for all values of I if the rotor model is exactly observed. The plot of $b_{I,I-2}$ shows that this is well reproduced for actinide nuclei.



There is a general trend between transition strength and transition energy for $2^+ \rightarrow 0^+$ transitions in even-even nuclei. NOTE: This is a log-log plot.

On this plot, our actinide nuclei have the highest transition strengths and lowest transition energies.

Q: Why should there be such a trend?



Transition strengths indicate how probable an electromagnetic decay is. Weisskopf made an estimate for the decay strength for a single proton transition. This is our yardstick for transition strengths - the Weisskopf unit (W.u.).

We can calculate transition strengths in W.u. for E2 transitions from the following formula:

$$B(E2) = \frac{9527}{E_\gamma^5 T_{1/2}(\gamma) A^{4/3}}$$

where E_γ is in MeV and $T_{1/2}$ in ps.